

# Planets around extreme horizontal branch stars

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**Abstract.** We review three main results of our recent study:

- We show that a proper treatment of the tidal interaction prior to the onset of the common envelope (CE) leads to an enhance mass loss. This might increase the survivability of planets and brown dwarfs that enter a CE phase.
- From the distribution of planets around main sequence stars, we conclude that around many sdB/sdO stars more than one planet might be present. One of these might have a close orbit and the others at about orbital periods of years or more.
- We show that the intense ionizing flux of the extreme horizontal branch star might evaporate large quantities of a very close surviving substellar object. Balmer emission lines from the evaporated gas can be detected via their Doppler shifts.

**Keywords:** planets, Horizontal Branch

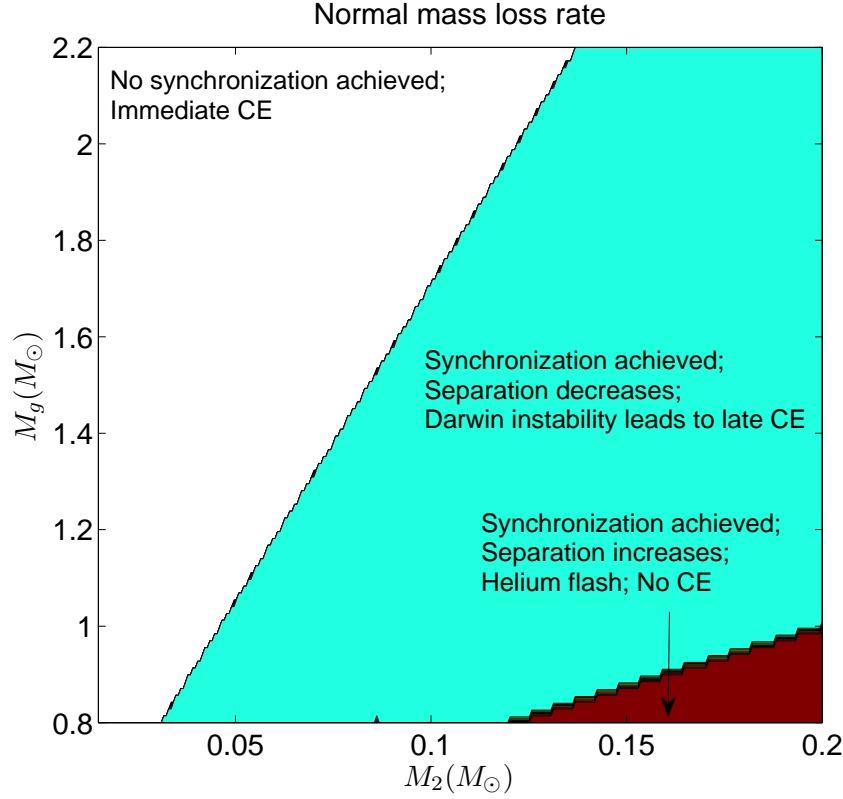
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## INTRODUCTION

EHB (Extreme Horizontal Branch) stars are hot, small, helium burning stars. In order to become EHB the RGB progenitor must lose most of its envelope. For the purpose of these proceedings there will be no differentiation between sdB, sdO (which are the spectroscopical classes) and EHB stars (the photometric definition). It is known that planets can exist around sdB stars. In many cases it is possible that planets are responsible for the formation of the EHB star, e.g. HD 149382 b [6]. In these proceeding we will review three main topics: In section 1, we will discuss the interaction of brown dwarfs or low main sequence stars and the RGB progenitor. Our goal is to study in more detail the evolution of binary systems in a stage prior to the onset of the CE phase, and in particular systems that have reached synchronization; the synchronization is between the orbital period and the primary rotation period. In section 2 we will discuss the bimodal distribution of planets, and the implications to EHB stars. In section 3 we will discuss planet evaporation, and detection of  $H\alpha$ , and  $H\beta$  emission. In section 4 we will summarize our concussions.

## INTERACTION BETWEEN BROWN DWARFS OR LOW MAIN SEQUENCE STARS AND THE RGB PROGENITOR

We start our calculation when the primary stellar radius has increased enough for tidal interaction to become significant. For the binary systems we study, where the primary is an RGB star and the secondary is a low-mass main sequence (MS) star or a brown dwarf,

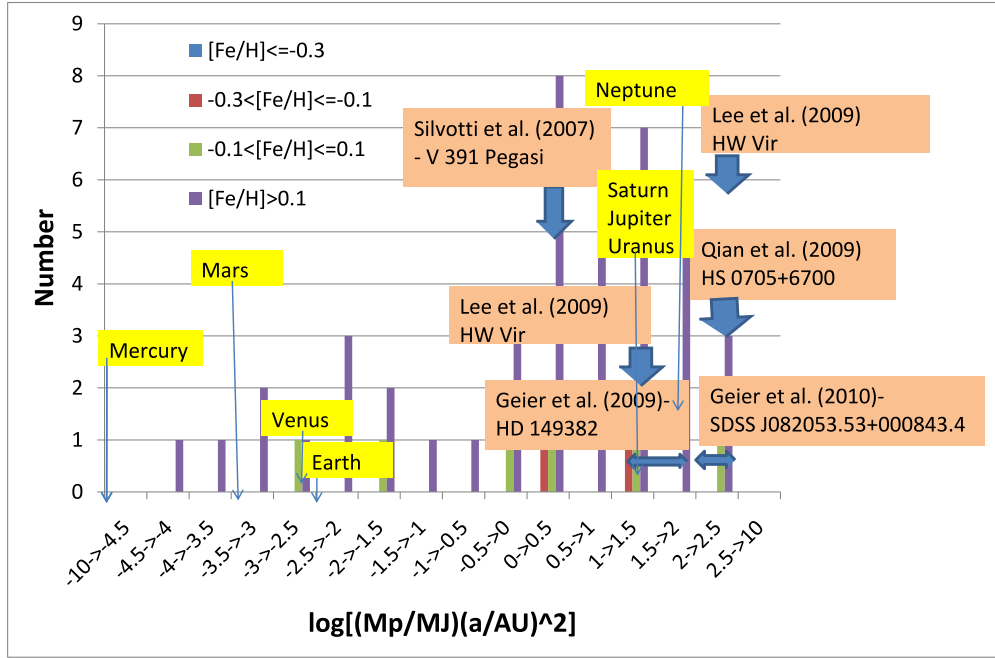


**FIGURE 1.**  $M_g$  vs.  $M_2$  representing binary systems that reached or did not reach synchronization. Our normal mass-loss rate of  $\eta_R = 3 \times 10^{14}$  was used (for details see Reimers 18, & Bear & Soker 1). The initial core mass is  $M_c(0) = 0.4M_\odot$ , and the initial (primordial) orbital separation prior to tidal interaction is  $a_0 = 5R_g(0) = 405R_\odot$ . Calculation is terminated as indicated, when one of the following occurs: The Darwin instability brings the system to a CE phase (marked Darwin Instability); The core mass reaches  $0.48M_\odot$  and assumed to go through a core Helium flash (Helium flash). The two other channels: (1) A total depletion of the RGB envelope. (2) The RGB stellar radius exceeds the orbital separation ( $R_g = a$ ), do not occur for the case presented here.

tidal interaction becomes important when the giant swells to a radius of  $R_g \sim 0.2a$ , where  $a$  is the orbital separation and  $R_g$  is the giant radius [20]. The primary radius increases along the RGB as the core mass increases. The primary and the secondary initial masses range in the binary systems we study are  $0.8M_\odot \leq M_1 \leq 2.2M_\odot$ , and  $0.015M_\odot \leq M_2 \leq 0.2M_\odot$ , respectively.

When a binary system starts its evolution it is not synchronized, and therefore tidal interaction will lead to a fast spiraling-in process. The binary system can then either reach a synchronization or stays asynchronous. In systems that maintain synchronization two opposing forces act: On one hand in order to maintain synchronization the secondary transfers, via tidal forces, orbital angular momentum to the envelope, and the orbit shrinks. On the other hand mass loss acts to increase orbital separation. If orbital separation increases faster than the RGB stellar radius, no Common Envelope (CE) will occur either due to total envelope loss or to a Helium flash. However, if orbital separation





**FIGURE 3.** Number of planets vs.  $\log \left[ \frac{M_p}{M_J} \left( \frac{a}{AU} \right)^2 \right]$ . The planets shown here are multi planet systems for stars in the mass range of  $1M_{\odot} \leq M_{\text{star}} \leq 1.5M_{\odot}$ , plus the planets of our solar system.

tend on average to harbor closer planets. Soker & Hershenhorn (2007) had 207 planets in their analysis. We repeated their analysis using 331 planets (out of more than 400 that were discovered so far) and got similar results. In figure 2 only the multi-planet systems from the research are represented (for more details see Bear & Soker 2).

The planets shown in this figure are all part of a multi-planet systems (two planets or more that orbit the same star). All central stars are in the mass range of  $1 - 1.5M_{\odot}$ , this mass is the typical mass of the progenitors of EHB stars (for more details see Bear & Soker 2). In general, there are two groups of planets, the inner marked by (I), and the outer planets that are marked by (O). In order to implement this distribution to EHB stars we will review the observations of planets around EHB stars:

Geier et al. (2009) announced recently the discovery of a close substellar companion to the hot subdwarf (EHB) star HD 149382. The orbital period is very short, 2.391 days, implying that the substellar companion had evolved inside the bloated envelope of the progenitor RGB star (a CE phase). The mass of the companion is  $8 - 23M_J$ , so either it is a planet or a low mass brown dwarf. This discovery supports the prediction of Soker (1998) that such planets can survive the common envelope (CE) phase, and more relevant to us, that planets can enhance the mass loss rate on the RGB and lead to the formation of EHB.

However, Jacobs et al. (2010) analyzed He lines and found no evidence for the presence of this claimed planets. This debate will soon be resolved by further observations. Other planets that orbit EHB at larger separations have been detected (Silvotti et al. 19, Lee et al. 15 & Qian et al. 17). Silvotti et al. (2007) announced the detection of a planet

with a mass of  $3.2M_J$  and an orbital separation of  $1.7AU$ , around the hot subdwarf V391 Pegasi. Serendipitous discoveries of two substellar companions around the eclipsing sdB binary HW Vir at distances of  $3.6AU$  and  $5.3AU$  [15] and one brown dwarf around the similar system HS 0705+6700 with a period of  $2610d$  and a separation of  $< 3.6AU$  [17]. Recently Geier et al. (2010) discovered a brown dwarf companion to the hot subdwarf SDSS J083053.53+0000843.4. This system contains an sdB star with an approximated mass of  $0.25 - 0.47M_\odot$ . A brown dwarf of  $0.045 - 0.067M_\odot$  orbits this sdB with an orbital period of  $0.096d$ . Due to its close orbit it is very likely that this system went through a Common Envelope phase.

All of these five systems are present in the graph, with their evaluated orbital separation around the progenitor of the EHB star [2]. It is quite plausible that closer planets did interact with the RGB progenitor of the sdB star; they are not observed in these systems. We end by noting that all these substellar companions have been detected in the field. The main conclusions we can draw from figure 3 are as follows: Planets are expected in a double peak distribution. Outer planets can survive the evolution. In particular, inner planets in the same system that were engulfed, saved the outer planets by enhancing mass loss rate early on the RGB. The inner planet might survive the CE phase and be found around the EHB star, but only if massive enough  $M \geq 10M_J$ .

## PLANET EVAPORATION AND DETECTION

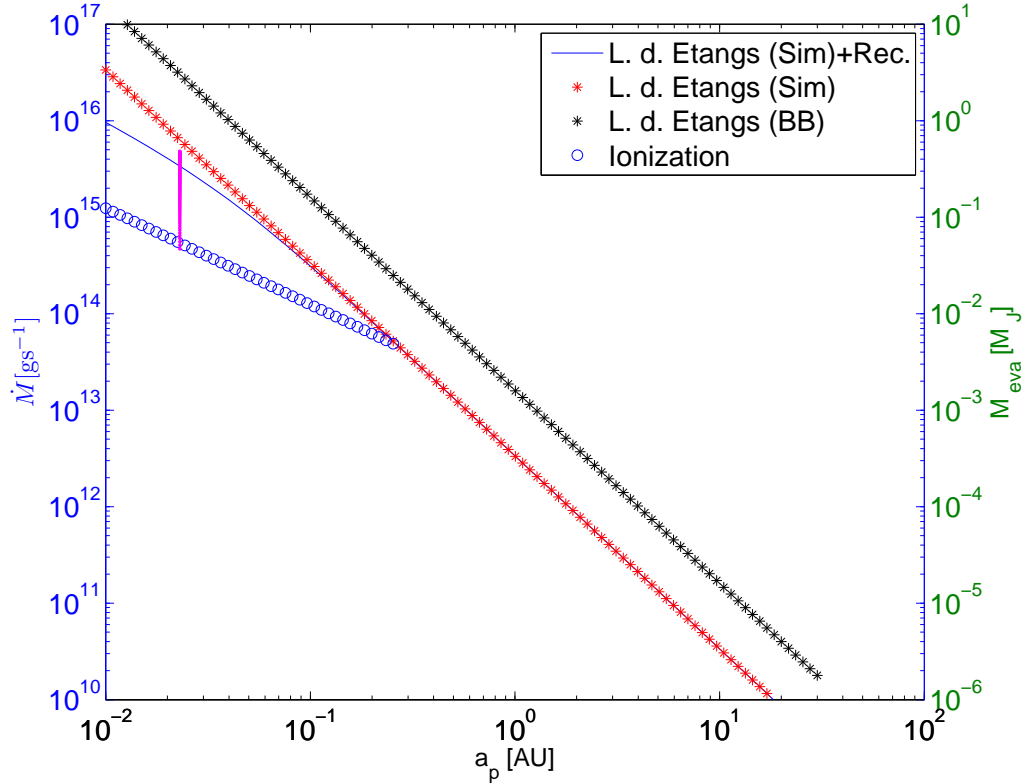
We study the evaporation of planets orbiting EHB stars. We adopt the simple model presented by Lecavelier des Etangs (2007) which represents the blow-off mechanism [5] and investigate the implications for a planet orbiting an HB star (this model is similar to the energy limited model purposed by Murray-Clay (2009)). We refer to the ionization model as well as a lower limit for the mass loss from the planet (for details see McCray & Lin 14).

When the central source is hot a large fraction of the radiation is energetic enough to ionize the evaporated gas. The evaporated gas recombines and emits at longer wavelength, a radiation that escapes from the planet's vicinity. Although recombination is not relevant to planet around solar-like stars, its role becomes more important for hot HB stars and central stars of planetary nebulae. We assume that:

- Most of the evaporated gas flows toward the radiation source.
- The central star keeps the gas almost fully ionized.
- The ionizing photons of the parent star that are absorbed by the evaporated gas are removed from the radiation that heat the star.
- All the radiation emitted by the recombining gas escape.
- We assume that the gas flows with the escape velocity from the planet.

The recombination rate is proportional to the density square, hence to mass loss square. We solve the mass loss rate of Lecavelier des Etangs (2007) taking into account the recombination. Substituting numerical values gives

$$\dot{m}_{p0} > 5 \times 10^{15} \left( \frac{\beta}{0.5} \right) \left( \frac{v_{\text{esc}}}{250 \text{ km s}^{-1}} \right)^4 \left( \frac{R_p}{0.1 R_\odot} \right) \left( \frac{e_\gamma}{20 \text{ eV}} \right)^{-1} \text{ g s}^{-1}. \quad (1)$$



**FIGURE 4.** Mass evaporation rate  $\dot{m}_p$  (left axis) versus the orbital separation  $a_p$ . The right axis gives the total mass that would be evaporate during a period of  $6 \times 10^7$ yr. The blue circles (lower line) represent the ionization model (for details see Bear & Soker 2010). The black thick (upper) line represents the evaporation rate based on Lecavelier des Etangs (2007) for a black body energy distribution. The red thick line represents the evaporation rate based on Lecavelier des Etangs (2007) for a self consistent calculated spectrum of HD 149382 [10]. The blue thin line represents the same model of Lecavelier des Etangs (2007) with recombination of the evaporated gas included (eq. 1) for a self consistent calculated spectrum of HD 149382 [10], instead of a black body that is not accurate at wavelengths below 1200Å. The evaporation rates are calculated for an EHB central star and a planet with the properties of the HD 149382 system:  $T_{\text{EHB}} = 35500\text{K}$ ,  $M_{\text{EHB}} = 0.5M_{\odot}$ ,  $R_{\text{EHB}} = 0.14R_{\odot}$ ,  $M_p = 15M_J$  [6] and  $R_p = 0.1R_{\odot}$ . The orbital separation of this system is  $a_p = 5 - 6.1R_{\odot}$ , but here it is an independent variable. The magenta line represents an orbital separation of  $a_p = 5.5R_{\odot}$ .

Where  $4\pi\beta$  is the solid angle to where the evaporation flow occurs with  $\beta = 0.5$ ,  $v_{\text{esc}}$  is the escape velocity of the gas,  $R_p$  is the planet radius and  $e_{\gamma} \sim 20\text{eV}$  is the average energy of the ionizing photons. Figure 4 represents the different mass loss considered and the mass loss that takes into account recombination. These are calculated with the appropriate spectrum as was calculated for HD 149382 [10]. For comparison we show the evaporation rate for a BB (Black Body) spectrum with the same effective temperature and luminosity (black upper line, for details see figure caption).

The properties of the EHB central star and the planet are taken to be those of the HD 149382 system (Geier et al. 6; see figure caption). The orbital separation of this system is  $a_p = 5 - 6.1R_{\odot}$ , but in the figure this is an independent variable. On the right axis of

figure 4 we give the total mass that would be evaporate during a period of  $6 \times 10^7$  yr, about the duration of the HB phase, with the same mass loss rate given on the left axis. We will concentrate on the orbital separation range of  $a_p = 0.01 - 5AU$ .

The calculation of the  $H\alpha$  luminosity from the evaporated gas is done in the following way, starting with the following assumptions:

1. The evaporation is mainly into a solid angle  $4\pi\beta$ .
2. Close to the planet, where most of the recombination occurs, the material flows at the escape speed from the planet.
3. For typical values we find the medium to be optically thin to  $H\alpha$ .
4. We assume that the evaporated gas is almost completely ionized. Any recombination that occurs is balanced by the incoming photons from the EHB star.
5. Most of the recombination and the  $H\alpha$  source occur at a relatively high density of  $n \simeq 10^{10} - 10^{12} \text{cm}^{-3}$ . At such densities collision between atoms change the amount of energy that is channelled to  $H\alpha$ . In our simple treatment we take the recombination coefficient neglecting the dependence on density. We note that Bhatt (1985) calculates the  $H\alpha$  emission from a destructed comet. He estimates the density to be  $\sim 10^{13} \text{cm}^{-3}$  and neglects the dependence on density. Korista et al. (1997) found that the dependence in density on this high densities is negligible.

The  $H\alpha$  energy released due to recombination is

$$L_{H\alpha} = \int_{R_p}^{\infty} \alpha_H(h\nu_{H\alpha}) n_e n_p dV \quad (2)$$

Solving the integral yields

$$L_{H\alpha} \sim 3 \times 10^{29} \left( \frac{\dot{M}}{10^{16} \text{g s}^{-1}} \right)^2 \left( \frac{\beta}{0.5} \right)^{-1} \left( \frac{R_p}{0.1 R_{\odot}} \right)^{-1} \left( \frac{v_{\text{esc}}}{250 \text{km s}^{-1}} \right)^{-2} \text{erg s}^{-1}. \quad (3)$$

We find equivalent width of  $EW_{\alpha} \sim 0.05A$  for the  $H\alpha$  emission and  $EW_{\beta} \sim 0.006A$  for the  $H\beta$  emission, both for the calculated spectrum of Heber [10].

Although the EWs are not high, their periodic variation might ease the detection of the line. At an orbital separation of  $5.5R_{\odot}$  the orbital velocity of the substellar companion is  $130 \text{km s}^{-1}$ . Therefore, during the orbital period the center of the emission by the evaporated gas might move back and forth over a range of up to  $\sim 5.5A$  and  $\sim 4.0A$ , for the  $H\alpha$  and  $H\beta$  emission lines, respectively. These EWs are an upper value since they are based on the black body distribution. We conclude that it might be possible to identify a planet via the  $H\alpha$  emission of its ablated envelope.

## SUMMARY AND CONCLUSIONS

We find that the pre CE evolution is crucial in understanding binary systems where the primary star is an evolved red giant branch (RGB) star, while the secondary star is a low-mass main sequence (MS) star or a brown dwarf. Moving to planets, from studying the distribution of planets we see that they are expected in a double peak distribution.

Outer planets can survive the evolution of the progenitor of the EHB. In particular, inner planets that were engulfed by the RGB progenitor might “saved” the outer planets by enhancing mass loss rate early on the RGB. With the enhanced mass loss rate the RGB star will form an EHB star. We also saw in section 3 that planets close to an EHB star might be detected through  $H\alpha$  and  $H\beta$  emission.

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